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Land-water-energy nexus of sugarcane production in Thailand

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ABSTRACT

Agriculture is a key economic sector for developing countries confronting challenges on the over-exploitation of land and water resources for food and biofuels crop production. Sugarcane is recognized as a promising crop serving both food and bioenergy needs that are being promoted leading to expansion of the plantation areas. The study assesses the land-water-energy nexus of irrigated and non-irrigated sugarcane production systems in the Chao Phraya and Chi watersheds of Thailand using carbon footprint, ecological footprint, and water scarcity footprint. The results indicate that freshwater resource is essential to sugarcane productivity improvement. Irrigation helps increase the sugarcane yields around 23–54% as compared to the non-irrigated system; the carbon and ecological footprint of sugarcane products are also consequently decreased by around 11–36% and 15–35%, respectively. Nevertheless, the water scarcity potential would be increased. Hence, the efficient irrigation technology like drip irrigation is an important factor to drive sustainable sugarcane production in the future. Land-water-energy nexus management measures for improving sustainability of sugarcane production are also recommended.

1. Introduction

Agriculture is known as the key economic sector for developing countries vis-à-vis their socio-economic development; human well-being and economic prosperity of people rely heavily on the development of agro-industry supply chains. The rapid development nowadays raises the demands for food, feed and fuels, and brings about increased concerns on the competition between land, water and energy resources as well as consequences on greenhouse gases (GHG) emissions. The demands for freshwater, land, and energy for food have been projected to increase significantly in the next decades due to population growth, urbanization and economic development (Hoff, 2011). Water crises have become one of the top five key global risks over the past five years (2011–2016) as reported by the World Economic Forum (WEF, 2017). Meanwhile, agriculture is the most freshwater consumptive sector accounting for around 85% of global freshwater consumption (Hoekstra and Chapagain, 2007). To meet the global demands for food in 2050, food production needs to be increased by about 60% (FAO, 2011). This has raised concerns on water scarcity caused by the over-exploitation of water for food and biofuels along with climate change effects (Zhang et al., 2013; Gheewala et al., 2014, 2017). In view of the impact from climate change, food production accounted for 19–29% of the global anthropogenic GHG emissions, 80% of which was from agriculture (Vermeulen et al., 2012). The promotion of biofuels to substitute fossil fuels will induce more requirements for land and water resources which in turn will compete with food production systems (Popp et al., 2014). In addition, increasing crop production either by intensification of agriculture or by expansion of land can lead to increase in GHG emissions (Tilman et al., 2002; Searchinger, 2010). The volatility of water and food prices are also anticipated due to the increased production of bioenergy (World Bank, 2008; Peri et al., 2017). All these issues indicate that the interrelationships of land, water, energy and crop production systems need to be understood by the decision makers to formulate appropriate policy measures for enhancing the efficient use of these resources (Flammini et al., 2014; Rasul and Sharma, 2016). However, to formulate the appropriate policy measures especially for agriculture, it is necessary to investigate specifically for each region by considering the local context such as geographical and climate conditions, irrigation infrastructure, local freshwater resource availability as well as farming practices.

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Sugarcane is a major crop grown in the tropical and subtropical regions and is nowadays recognized as an outstanding crop serving for both food and bioenergy production because of its high proportion of biomass in both solid and liquid forms. It was estimated that around 1.8 billion tonnes of sugarcane biomass were produced from more than 100 countries around the world in 2012 (Souza et al., 2015). Brazil is the world's largest sugarcane producing country with around 736 Mt/y contributing about 39% of the global sugarcane production, followed by India (19%), China (6%) and Thailand (6%), respectively. With a total sugarcane production of about 94 Mt/y and sugar export of about 6.5 Mt in 2016, Thailand has become the world's second largest sugar-exporting country (OAE, 2016). The sugarcane plantation areas have on average increased about 3% per year from year 2005–2015 with about 1.65 M ha in 2016 (OAE, 2016). Currently, bioethanol production in Thailand is about 3.2 ML/day with around 59% from sugarcane molasses along with 3% directly from sugarcane juice. However, the Alternative Energy Development Plan 2015 (AEDP) of the government has set the goal for bioethanol production in the country to be about 11.3 ML/day in the year 2036 (DEDE, 2015). This has brought about the requirement for boosting productivity of sugarcane cultivation in the country to fulfill the demands for sugarcane as biofuel feedstock.

The expansion of sugarcane plantation areas by substituting the low-productivity paddy fields has also been introduced as an option to increase farmers' income, reduce water consumption and to fulfill the excess capacity of the existing sugar mills. Nevertheless, from the nexus point of view as mentioned earlier, the expansion of sugarcane cultivation in different regions can bring about a difference in the scale of impacts on land, water and GHG emissions depending on factors such as soil condition, rainfall, water stress situation, agricultural practices and productivity. There have been several carbon and water footprint studies of sugarcane cultivation carried out in Thailand in the last few years (Pongpat et al., 2017; Gheewala et al., 2014; Yuttitham et al., 2011); however, most of the studies were single-issue based thus not capturing the trade-off among the impacts on land, water, energy and GHG emissions. Moreover, the scarcity situation of resources such as freshwater in the sugarcane cultivation areas was not taken in account in the studies so far. This study therefore aims to assess the land-water-energy nexus of different sugarcane production systems in two regions of Thailand where the expansion of sugarcane is being promoted. The local water scarcity index of different regions where the sugarcane is grown is specifically considered. The trade-off between the impacts on land, water use, and GHG emissions due to different farming practices are determined using a set of indicators including carbon footprint, ecological footprint, water consumption and water scarcity footprint in order to provide the recommendations for improving the sugarcane production system.

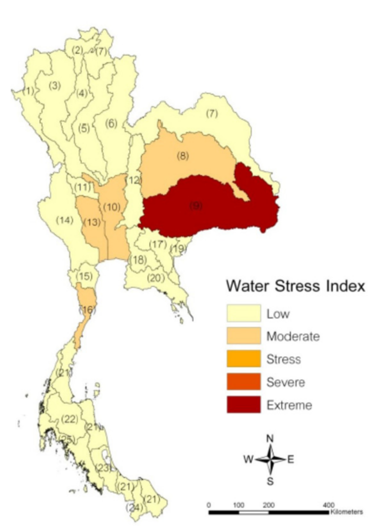
2. Materials and methods

2.1. System boundary of the assessed sugarcane cultivation systems

Thailand is located in the South Eastern region of Asia; the country's climate is mainly tropical i.e. exhibiting hot and humid conditions throughout the year, where sugarcane can be grown well. The studied areas are the sugarcane cultivation systems in two provinces i.e. Nakhon Sawan and Chaiyaphum representing the Chao Phraya and Chi watersheds, respectively. The Chao Phraya watershed mainly covers the central and some parts in northern Thailand. The total area of the Chao Phraya watershed is 20,266 km^2 covering 11 provinces including Nakhon Sawan, Chai Nat, Sing Buri, Lop Buri, Ang Thong, Ayutthaya, Saraburi, Pathum Thani, Nonthaburi, Samut Prakan and Bangkok. The average annual rainfall of this watershed is approximately 1140 mm with around 3786 million m^3 accounted for as the average annual runoff. Around 60% of the cultivated area in the Chao Phraya watershed is irrigated. On the other hand, the Chi watershed is located in north eastern Thailand, and is a part of the Mekong river basin. The total area of the Chi watershed is 49,130 km^2 covering 12 provinces including Khon Kaen, Chaiyaphum, Kalasin, Maha Sarakham, Roi Et, Yasothon, Ubon Ratchathani, Nakhon Ratchasima, Loei, Nong Bua Lam Phu, Udon Thani and Si Sa Ket. The average annual rainfall in this watershed is approximately 1208 mm with around 11,160 million m^3 accounted for as the average annual runoff. It was found that only 12% of the cultivated areas in Chi are under irrigation. Those two regions were selected as the studied areas for comparison because the infrastructure like irrigation systems, water resource availability, water stress situation, agricultural practices and socio-economic of farmers are different. Fig. 1 shows the water stress index (WSI) for the 25 major river basins of Thailand. The WSIs were estimated using the Annual Water Withdrawal to Annual Water Availability ratio. The results indicated that currently the Chi watershed has more water stress than the Chao Phraya watershed as indicated by the WSI values of about 0.471 and 0.339, respectively (Gheewala et al., 2014).

Sugarcane is newly planted once and then harvested repeatedly after 12 months of growth for 3–4 years. Fig. 2 shows the system boundary of sugarcane cultivation systems which can be classified into four main stages i.e. land preparation, planting, treatment and irrigation, and harvesting. The reference unit for the footprint assessments of sugarcane is set as a tonne of sugarcane product. Land preparation includes the step of ploughing by riper, two or three times of disk ploughing and disk harrowing. For provinces like Nakhon Sawan in the Chao Phraya watershed, the land is generally prepared and the sugarcane planted in November to December and harvested in December to January of the following year. Water is normally required since the beginning of planting using irrigation system such as furrow irrigation. However, for the northeastern region, like in the Chi watershed, planting is in the rainy season for which land clearing starts in April and harvesting is around January to March of the following year.

Planting, nowadays mostly mechanized, is carried out by billet planters. Chemical fertilizers and agrochemicals such as herbicides and insecticides are used in varying amounts depending on



Watersheds	WSI
(1) Salawin	0.017
(2) Kok	0.018
(3) Ping	0.023
(4) Wang	0.021
(5) Yom	0.044
(6) Nan	0.015
(7) Khong	0.014
(8) Chi	0.471
(9) Mun	0.927
(10) Chao Phraya	0.339
(11) Sakae Krang	0.031
(12) Pasak	0.050
(13) Tha Chin	0.287
(14) Mae Klong	0.018
(15) Phetchaburi	0.022
(16) West Coast Gulf	0.158
(17) PrachinBuri	0.016
(18) Bang Pakong	0.026
(19) Thole Sap	0.019
(20) East-Coast Gulf	0.015
(21) Peninsula-East coast	0.067
(22) Tapi	0.060
(23) Thale sap Songkhla	0.014
(24) Pattani	0.025
(25) Peninsula-West coast	0.012

Fig. 1. Water stress index classified by 25 watersheds of Thailand (Gheewala et al., 2014).

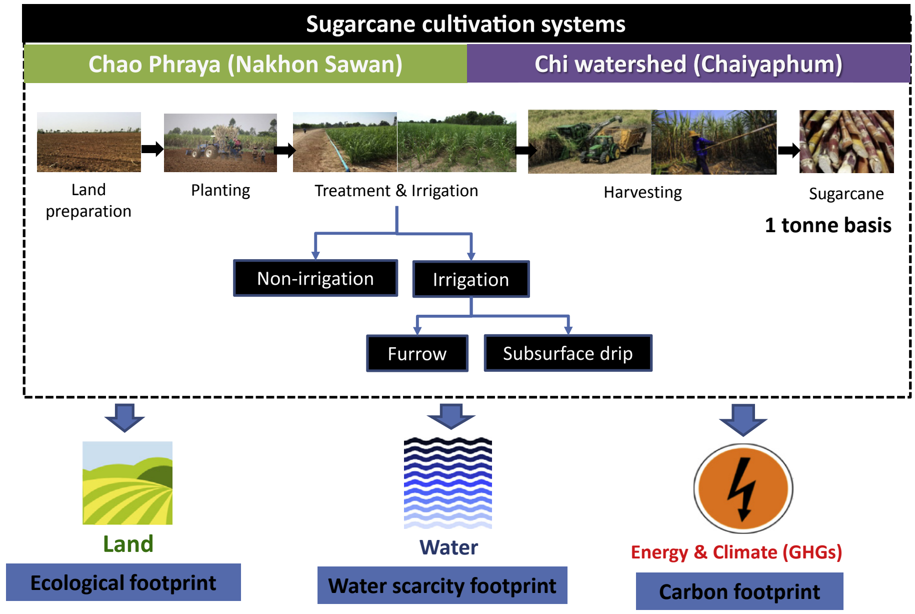


Fig. 2. System boundary of nexus assessment.

farmers' practices. The most common irrigation system used is furrow irrigation. Harvesting begins 10–14 months after planting. However, mechanized harvesting is currently gaining attention by farmers as well as the sugar millers due to the lack of farm workers. Nevertheless, manual harvesting along with cane trash burning before harvesting is still the common practice sharing about 70% of total harvested sugarcane going into the mills.

2.2. Nexus assessment approaches

The Water-Energy-Food nexus assessment approach has been proposed as the way to enhance efficiency and balance the different uses of the ecosystem resources like land, water and energy by various stakeholders in a particular region (Flammini et al., 2014; Azapagic, 2015; Sanders and Masri, 2016; Smajgl et al., 2016). The benefits of the nexus approach are to improve resource use efficiency along with economic efficiency and livelihood options (Bazilian et al., 2011). There is a variety of approaches to assess the WEF nexus e.g. life cycle based-approached like water footprint as well as the full life cycle assessment (LCA) (Vanham, 2016; Scholz et al., 2015; Jeswani et al., 2015; Brancoli et al., 2017), simulation and optimization (Garcia and You, 2016), and numerical modeling/econometrics/economic modeling (Jalilov et al., 2016; Pacetti et al., 2015). Nevertheless, there are still gaps in applying nexus assessment for policy recommendations because the results from a study in one location may not be able to be used for policy recommendations in another location since the arable land and freshwater resources are limited by geographical conditions.

Nowadays, the life-cycle based evaluation approaches for single environmental issues such as carbon footprint, water footprint and ecological footprint have gain attention worldwide (Finkbeiner et al., 2010). Each footprint indicator generally has its own focus and way of interpretation. Hence, to assess the nexus on land, water, energy and GHGs that occurs from anthropogenic activities such as agriculture, it is necessary to understand the scope of the each footprint and how its indicator links to the resources used and GHG emissions. For example, somehow, an indicator like ecological footprint can be used to explain the land-energy-climate change nexus from the agricultural activities because the indicator will account both land occupation for crop growing and the carbon dioxide emissions from fossil energy used for machines. However, this inclusion of carbon dioxide emission in ecological footprint may not be enough to capture some important impacts on climate change from agricultural activities such as the non-CO_2 GHG emissions like N_2O caused by fertilizers application, and CH_4 from burning of agricultural biomass e.g. cane trash burning. Those non-CO_2 GHG emissions will be completely taken into account only when performing the carbon footprint. Moreover, the water scarcity impact from agriculture, which is an important issue for agriculture, will not be explained unless the water scarcity footprint is also conducted. Hence, to understand the land-water-energy nexus of agriculture for the better management of land, water and energy used in the future, those three footprints need to be considered together in the nexus assessment even though there is some overlap between them. This section therefore aims to determine the impacts of agriculture on each footprint indicator by classifying into the key resources of interest for agriculture i.e. land use, water use, agrochemicals use, and energy use.

In this study, the life cycle approach has been used to account the total direct and indirect effects of sugarcane production systems on land, water and climate change in the terms of "Footprint" indicators. The footprint assessment will help quantification of the environmental burdens including greenhouse gas emissions, biologically productive land use and freshwater consumption caused by different sugarcane production systems in Thailand. Fig. 3 shows the simplified land-water-energy-climate nexus in agriculture.

2.2.1. Ecological footprint

The ecological footprint (EF) is a measure of the area of biologically productive land and water that is required for an individual or an activity to produce all the resources it consumes and to absorb the waste it generates, using prevailing technology and resource management practices (Wackernagel and Rees, 1997). However, in the concept of LCA, the ecological footprint of a product is defined as the sum of time-integrated direct land occupation and indirect land occupation for capturing CO_2 emissions from fossil energy use and cement burning (Huijbregts et al., 2008). In this study, the ecological footprint of sugarcane cultivation is scoped as

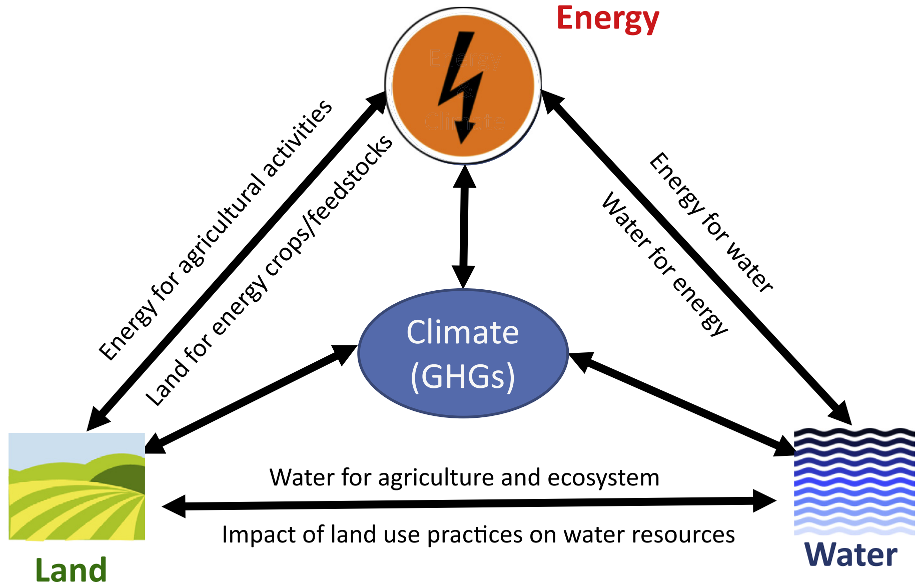


Fig. 3. Simplified land-water-energy-climate nexus in agriculture.

the sum of direct land occupation (EF_{direct}) and indirect land occupation (m^2a) related to CO_2 emissions from fossil energy use (EF_{CO2}) (Frischknecht et al., 2007) as shown in Equation (1).

$$EF = EF_{direct} + EF_{CO2} \tag{1}$$

For interpretation, the study classified the ecological footprint result into two categories i.e. direct ecological footprint which refers to the direct land occupation for sugarcane cultivation, and the indirect ecological footprint which refers to the indirect land occupation for the production of material used during sugarcane cultivation and indirect land occupation for capturing atmospheric CO_2 emissions from fossil fuel combustion.

2.2.2. Water scarcity footprint

Water footprint is a metric that quantifies the potential environmental impacts related to water as defined by the International Organization for Standardization (ISO) in ISO 14046. In this study, the direct water use for sugarcane cultivations in the Chao Phraya and Chi watersheds is accounted by separating into rainwater and irrigation water. Since the water scarcity impact from water use will be different depending upon not only the amount of water consumed but also the water stress level in the area where the water was extracted, the water scarcity footprint has therefore been applied in the study. The water scarcity footprints of sugarcane cultivation in the two different regions can be evaluated based on the "water stress index (WSI)" of the 25 watersheds of Thailand (Gheewala et al., 2014) as indicated in Equation (2). The water scarcity footprint is measured in terms of "m^3 H_2Oeq". This water scarcity footprint value implies the amount of water deficiency to downstream human users and ecosystems. A low water scarcity footprint indicates lower impacts on water consumed (Pfister et al., 2009). The study classified the water scarcity footprint result into two categories i.e. direct water scarcity footprint which refers to the water scarcity impact potentially caused by the direct irrigation water use during sugarcane cultivation; meanwhile, the indirect water scarcity footprint refers to the water scarcity impact potentially caused by the water use from raw materials production. The water scarcity indicator for raw materials used characterization factors from Pfister et al. (2009) in SimaPro 8 software.

$$\begin{aligned}&\text{Water Scarcity Footprint}_{\text{sugarcane,region i}}\\&\quad = \text{Irrigation water use}_{\text{sugarcane,region i}} \times \text{WSI}_{\text{region i}}\end{aligned} \tag{2}$$

Prior to determining the water scarcity footprint, firstly, the crop water use (WU_c) is determined using Equations (3) and (4). Crop water use, denoted as crop evapotranspiration (ET_c), refers to the volume of water lost via evapotranspiration including evaporative water from soil and crop surfaces and transpired water from crop to atmosphere. Equation (3) shows the general formula to estimate ET_c [mm/day] which consists of two terms i.e. weather and crop specifics for crop cultivated in different locations (Allen et al., 1998). K_c represents crop coefficient [dimensionless], and ET_0 represents the reference Penman-Monteith crop evapotranspiration [mm/day]. The ET_0 for each province and the crop coefficient (K_c) of sugarcane have been taken from the Irrigation Water Management Division (IWM), Royal Irrigation Department of Thailand (IWM, 2008, 2011). Equation (4) shows the formula to calculate the crop water use. The factor 10 is used to convert water depth in millimeters into water volume per land surface in m^3/ha. The summation will be done over the period from the day of planting (day 1) to the day of harvest (lgp stands for length of sugarcane growing period in days).

$$ET_c = K_c \times ET_0 \tag{3}$$

$$WU_c = 10 \times \sum_{d=1}^{lgp} ET_c\left(m^3/ha\right) \tag{4}$$

The procedure to classify the crop water use into rainwater and irrigation water is as follows: (a) calculating the (ET_c) for sugarcane grown in each region; (b) calculating the effective rainfall in each region during the sugarcane growing period; (c) the rainwater use for sugarcane can be evaluated by comparing the monthly evapotranspiration (ET_c) of sugarcane with the effective rainfall during the growing period. Then, if ET_c > effective rainfall, the rainwater used by sugarcane will be equal to the effective rainfall and then the "irrigation water requirement" in order to achieve the crop evapotranspiration of sugarcane can be estimated from "irrigation

water requirement" = ET_c - effective rainfall. However, if ET_c < effective rainfall, "irrigation water requirement" = 0. The study has also compared the amount of irrigation water requirement with the actual irrigation water used by farmers obtained from the field data.

2.2.3. Carbon footprint

Carbon footprint is an indicator showing the total amount of GHG emissions over the entire life cycle of a product or service and expressed in terms of "kg CO_2eq". The GHGs considered include both CO_2 and non-CO_2 gases. The characterization factors for converting one gram of N_2O and CH_4 emissions into CO_2eq are 298 g and 25 g of CO_2, respectively (IPCC, 2006). The general formula for determining the total GHG emissions of sugarcane cultivation is shown as Equation (5).

$$GHG_{Total} = GHG_{ec} + GHG_{field} + GHG_{td} \quad (5)$$

Where GHG_{Total} represents the total GHG emissions from the entire the life cycle of sugarcane cultivation (kg CO_2eq/t cane); GHG_{ec} represents the GHG emissions from the production of input materials including fertilizers and agrochemicals; GHG_{field} represents the GHG emissions occurring during the cultivation activities e.g. N_2O emissions from applied fertilizers and GHG emissions from combustion of fuels in agricultural machinery; GHG_{td} represents the GHG emissions caused by the transportation of raw materials used and transportation during the field operations.

2.3. Data sources

Primary data for sugarcane cultivation in the irrigated and non-irrigated areas are collected from sugarcane growers located in the Nakhon Sawan (Chao Phraya watershed) and Chaiyaphum (Chi watershed) provinces. The reference unit of the assessment is a tonne of sugarcane at farm gate. Primary data for sugarcane cultivation are collected from 30 sugarcane growers in two provinces i.e. Nakhon Sawan (covering planted areas around 350 ha) and Chaiyaphum (covering planted areas around 140 ha). There are two types of irrigation systems compared in the study i.e. furrow irrigation and subsurface drip irrigation. Fuel used for both irrigation systems is estimated based on 5.5 hp pump which is generally used by the sugarcane growers. The water pumping specification used in the assessment is about 1100 L/min and diesel consumption 2 L/hour. Table 1 shows the key input-output materials for the surveyed sugarcane plantations. The life cycle inventory (LCI) for the production of input fertilizers, agrochemicals, and fuels used are referred from the Thai national LCI database (MTEC, 2014) and the international life cycle inventory databases such as Ecoinvent (Ecoinvent, 2012).

The difference in the data of non-irrigated system in Chao Phraya and Chi such as the amount of organic fertilizer used and fuel consumption is due to the different farming practices. Sugarcane growers in the Chi watershed (northeastern region of Thailand) generally have low household incomes; thus, manure is highly relied on as a fertilizer. In addition, the farming practice is mainly manual for both planting and harvesting. On the other hand, sugarcane growers in the Chao Phraya watershed (central region) generally apply more chemical fertilizers as they have higher household incomes. In addition, there is more use of machinery for both sugarcane planting and harvesting due to lack of labor in the central region unlike in the northeastern region.

3. Results and discussion

3.1. Comparison of footprint indicators

Table 2 shows the water scarcity footprint, carbon footprint and ecological footprint results per tonne of sugarcane under irrigated and non-irrigated cultivation conditions in Nakhon Sawan (Chao Phraya watershed) and Chaiyaphum (Chi watershed). The results reveal that the irrigation system can help spur the yield of sugarcane as compared to the non-irrigated system by around 23% (Chaiyaphum) - 54% (Nakhon Sawan). One of the reasons that causes the irrigated sugarcane cultivation in Nakhon Sawan to have a higher yield improvement than Chaiyaphum is because the actual irrigation supplied by farmers in Nakhon Sawan is estimated to be

Table 1
Weighted average of input-output of the studied sugarcane cultivation systems.

	Inventory	Unit	Nakhon Sawan (Chao Phraya)		Chaiyaphum (Chi)	
			Irrigated	Non-irrigated	Irrigated	Non-irrigated
Sample sizes	Total planted areas	ha	163	184	48	90
Product	Sugarcane yields	t/ha	111	72	86	70
Land preparation	Diesel	L/ha	126	131	106	106
	Manure	kg/ha	–	23	315	1018
Planting	Diesel	L/ha	16	34	14	2
Treatment	N-fertilizer	kg/ha/y	58	102	104	57
	P-fertilizer	kg/ha/y	40	82	46	57
	K-fertilizer	kg/ha/y	26	60	85	56
	Urea	kg/ha/y	109	114	13	25
	Diesel (fertilizers & chemical applications including weed control)	L/ha/y	6 (manual & knapsack-type applicator)	3 (manual & knapsack-type applicator)	26 (mechanical application)	2 (manual & knapsack-type applicator)
	Diesel (irrigation)	L/ha/y	21 (furrow irrigation)	–	9 (subsurface drip irrigation)	–
	Agrochemicals	kg/ha/y	18	27	25	9
Harvesting	Diesel	L/ha/y	30	29	28	8
Transport	Truck 20t	t.km	4440	2880	3440	2800

Table 2
Ecological footprint, water scarcity footprint and carbon footprint of sugarcane production in different conditions.

Aspects	Indicators	Nakhon Sawan (Chao Phraya)		Chaiyaphum (Chi)	
		Irrigated	Non-irrigated	Irrigated	Non-irrigated
Crop yield	Sugarcane (t cane/ha)	111	72	86	70
Water use	Rain water (m^3/t cane)	68	105	66	81
	Irrigation water requirement (m^3/t cane)	34	52	67	82
	Actual irrigation water used (m^3/t cane)	17	–	32	–
	Water scarcity footprint (Direct) (m^3 H_2O eq/t cane)	6	–	15	–
	Water scarcity footprint (Indirect) (m^3 H_2O eq/t cane)	5	5	6	5
	Total Water scarcity footprint (m^3 H_2O eq/t cane)	11	5	21	5
Climate change	Life-cycle GHG emissions (kg CO_2eq/t cane)	30	47	32	36
Land	Ecological footprint (m^2a/t cane)	242	377	301	353
	Direct land occupation (m^2a/t cane)	197	303	256	313
	Indirect land occupation from raw materials (m^2a/t cane)	1	2	1	1
	Carbon dioxide (m^2a/t cane)	44	72	44	39

about 17 m^3/t cane which is closer to the irrigation water requirement of sugarcane i.e. 34 m^3/t cane (which was calculated from the crop evapotranspiration (ET) of sugarcane and the rainfall data in the region). Meanwhile, the actual irrigation supplied by farmers in Chaiyaphum is found to be around 32 m^3/t which still far from the irrigation water required for sugarcane growing in Chaiyaphum which is around 67 m^3/t cane. The furrow irrigation system was commonly found from the field survey in both provinces. However, nowadays, there is an increasing use of the higher efficiency irrigation systems such as the subsurface drip irrigation and big gun sprinkler by sugarcane growers in Thailand. This would help improve the water use efficiency for sugarcane cultivation in the future because the furrow irrigation has an irrigation efficiency of just about 55% while the subsurface drip irrigation has an efficiency of about 97% (OCSB, 2015).

The use of irrigation will increase the consumption of energy i.e. diesel, which in turn also induces additional GHG emissions per hectare. However, accounting for the yields improvement due to irrigation, the carbon footprint and ecological footprint of sugarcane product are decreased by around 11–36% and 15–35%, respectively. Nevertheless, the increased freshwater resources used for irrigation bring about an increase in the water scarcity footprint of irrigated sugarcane as also revealed by Table 2. The direct water scarcity footprint results of irrigated sugarcane in Nakhon Sawan and Chaiyaphum are about 6 and 15 m^3 H_2Oeq/t cane, respectively.

3.2. Environmental hotspots of sugarcane cultivations in view of footprint indicators

Table 3 shows the key hotspots on biological productive land use, water scarcity, energy use and GHG consequences that can be identified from the different footprints using the case of irrigated sugarcane cultivation in Nakhon Sawan province. For water scarcity footprint, the results show that direct irrigation water use is the main contributor to the impact on water scarcity potential accounting for about 57% of the total water scarcity footprint, followed by the indirect water scarcity footprint from agrochemicals and urea production which contributed about 19% and 11%, respectively. For ecological footprint, the results reveal that the direct arable land use for sugarcane cultivation contributes about 82% of the total ecological footprint, followed by the indirect impact from diesel fuel and urea fertilizer production which shared about 7% and 4%, respectively. The energy use in agricultural machines such as diesel is one of the key hotspots on the GHG emissions i.e. sharing about 21% of the total carbon footprint. However, the highest GHG emissions for sugarcane cultivation are from cane trash burning during sugarcane harvesting which is still the common practice for the small sugarcane growers in Thailand i.e. around 70% of total cane production in Thailand was found to be the burnt cane (OCSB, 2015). The N_2O emissions caused by the N-fertilizer application to the soil is also accounted in the carbon footprint and is one of the key contributors to the carbon footprint of sugarcane.

Table 3
Environmental hotspots of irrigated sugarcane cultivation in Nakhon Sawan province classified by water scarcity footprint, ecological footprint, and carbon footprint.

Process	Water scarcity footprint (m^3 H_2O eq./t cane)		Ecological footprint (m^2a/t cane)				Carbon footprint (kg CO_2eq/t cane)	
	Value	%[a]	Land occupation	CO_2	Total	%[a]	Value	%[a]
Direct agricultural land use	–	–	197	–	197	82%	–	–
Direct irrigation water use	6	57%	–	–	–	–	0.6	2%
Cane trash burning	–	–	–	–	–	–	10	33%
N_2O from N-fertilizer applied	–	–	–	–	–	–	3	11%
Diesel (excluding irrigation)	0.2	2%	0.0	16	16	7%	5.4	19%
Urea	1	11%	0.1	11	11	4%	4	14%
N fertilizer	0.5	5%	0.1	2	3	1%	1	3%
P fertilizer	0.5	4%	0.3	1	2	1%	0.6	2%
K fertilizer	0.1	1%	0.0	0.3	0.4	0%	0.1	0%
Agrochemicals	2	19%	0.1	5	5	2%	2	6%
Transport	–	–	–	8	8	3%	3	10%
Total footprint	**11**		**198**	**44**	**242**		**30**	

[a] % represents the contribution percentage of that process to the total footprint results.

3.3. Land-water-energy nexus management

The next step after the land-water-energy nexus assessment by footprint indicators is the nexus management which should be analyzed. As mentioned earlier, although there is a partial overlap between water scarcity footprint, ecological footprint and carbon footprint, none of these indicators alone can be used to explain the land-water-energy nexus of agriculture. The results revealed that the land-water-energy impacts directly come from the sugarcane cultivation stage i.e. land occupation and irrigation water use for sugarcane production. The indirect land-water-energy impacts caused by the materials and agrochemicals production as well as transportation are much lower than the sugarcane cultivation stage. To improve the efficiency of land use, water and energy during cultivation, treatment and harvesting of sugarcane should therefore be focused. The nexus management can be proposed as follows:

(1) The nexus assessment shows that the key linkage to the improvement on land, water, energy and GHG emissions performance of sugarcane cultivation is the promotion of an appropriate irrigation system. Freshwater resource is the vital factor for the crop's productivity improvement. However, in reality, the freshwater resource management for agriculture is a challenge for both the farmers and policy makers because the resource is limited to a certain area and period. The water management plan of the Royal Irrigation Department (RID) has reported that for agriculture in dry season, of the total sugarcane planted areas of about 68,670 ha in Chaiyaphum and 96,896 ha in Nakhon Sawan provinces, only 1% and 4% are under irrigation (RID, 2014). Expanding irrigation infrastructure entails a high cost for the government meanwhile, installing irrigation technology in the farm is a high cost to the sugarcane growers. Additionally, the freshwater resource has to be shared by many stakeholders in the region; therefore, the water user groups need to be set up and engaged for making a water management plan. This is quite a contrast to the land which generally the farmers will have their rights to use and manage; as well as the energy that farmers have their purchasing power for potentially unlimited use. However, nowadays, there is an increase in contract farming which would be helpful in terms of soft loans from sugar millers to their contract farmers for investing in irrigation systems as well as the mechanized farming system.

(2) The water use is found to be the key factor in land-water-energy nexus management of sugarcane. This is because, firstly, water is one of the key factors to improve the yield of sugarcane. The ecological footprint in view of direct land occupation could be reduced significantly for the case of irrigated sugarcane due to the higher yields as compared to non-irrigated case. At the same time, the additional energy use for irrigation is found to not significantly increase GHG emissions i.e. only around 2% of total carbon footprint of sugarcane as presented in Table 3. The challenge is only the irrigation infrastructure development for supporting sugarcane growers as well as the management of the remaining water availability in that area.

(3) High efficiency water irrigation system such as drip irrigation which is known to be the most precise and efficient to deliver water and nutrients to crops should be encouraged for sugarcane farmers. This is especially for the sugarcane planted areas located in the high water stress areas like in Chao Phraya, Chi and Mun watersheds of Thailand as revealed by Fig. 1. The furrow irrigation system which so far has been the common system used for irrigated sugarcane cultivation, has an irrigation efficiency of only about 55% (OCSB, 2015). Meanwhile, other irrigation systems like the big gun sprinkler, center pivot and subsurface drip irrigation have efficiencies of around 75%, 85% and 95%, respectively (OCSB, 2015). The irrigation water requirement for sugarcane cultivation in Nakhon Sawan and Chaiyaphum were estimated to be around 3736 m^3/ha and 5722 m^3/ha, respectively. To achieve the water requirement of sugarcane, using drip irrigation to substitute furrow irrigation will reduce the irrigation water use by about 2860 m^3/ha for the case of Nakhon Sawan province and 4380 m^3/ha for the case of Chaiyaphum province. Apart from the water use reduction, the diesel use for irrigation would be decreased which in turn leads to the reduction in carbon footprint. For example, the water scarcity footprint and carbon footprint of sugarcane for the case of Nakhon Sawan would be decreased from 11 to 9 m^3 H_2O eq/t cane and 30 to 29 kg CO_2eq/t cane, respectively if subsurface drip irrigation were used to substitute furrow irrigation.

(4) For agricultural zoning policy, so far, the land suitability is used as well as the rainfall; these are considered as the key criteria for identifying crops appropriate to each agricultural zone. However, due to climate change as well as the increased concerns on freshwater resource availability, the water stress index derived from the ratio of water demand and water availability in each region should be further taken into account for identifying areas to promote sugarcane. This is because the irrigation water must be one of the key factors for modern farming of sugarcane in the future, considering only the rainfall availability but not considering the existing or future demands on water in the region will affect water competition in the long run.

4. Conclusions

The combined use of the carbon, water scarcity and ecological footprints can give a more comprehensive picture of the land-water-energy nexus of agriculture. The different sugarcane cultivation systems in the Chao Phraya and Chi watersheds have been assessed using those three footprints. The study revealed that freshwater resources are the vital factor for improving sugarcane productivity. The irrigation system can help spur the yield of sugarcane as compared to the non-irrigated system by around 23% (Chaiyaphum) - 54% (Nakhon Sawan). Although the use of irrigation system will increase the consumption of energy i.e. diesel, which in turn also induces additional GHG emissions per hectare, however, accounting for the yields improvement due to irrigation, the carbon and ecological footprints of sugarcane are decreased by around 11–36% and 15–35%, respectively. The promotion of an efficient irrigation system is therefore an important factor to drive sustainable sugarcane production in the future because it helps improve the land, water and climate performance. The subsurface drip irrigation which has higher efficiency than existing furrow irrigation should be promoted as it would save the irrigation water by about 2860 m^3/ha for the case of Nakhon Sawan and 4380 m^3/ha for the case of Chaiyaphum. For policy makers, the water stress index which is derived from the ratio of water demand and water availability in each region should be further taken into account as one of the criteria to identify the suitable areas for future sugarcane expansion. Stakeholder engagement is required for the formulation of land-water-energy nexus management for agriculture in the future especially for the water resource management. The economic performance should further be integrated in the nexus assessment in order to identify and address the trade-off between

costs of investment, environmental burdens and the economic benefits from yield improvement.

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